

EFFECTS OF FOREST MANAGEMENT ON SNOW ACCUMULATION AND ABLATION
IN A MONTANE WATERSHED

by

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TABLE OF CONTENTS

1. INTRODUCTION AND BACKGROUND.....	1
Geographic Context, Forest Management, and Water Resource Risk	1
Snowpack Dynamics and Forest Structure	2
Snow Accumulation: Interception and Sublimation	2
Snow Ablation: Radiation and Energy Balance.....	4
Remote Sensing and Snowpack Monitoring Techniques.....	5
LiDAR for Snow Depth and Forest Structure.....	5
SAR for Snowmelt Onset.....	6
Study Purpose and Research Questions	7
2. METHODS	9
Snow Accumulation	9
Site for Snow Accumulation Data Collection.....	9
Snow Depth Data Collection and Analysis.....	11
Microclimate	13
Ablation.....	15
Study Site for Snow Ablation	15
Day of Onset Melt Data Acquisition.....	16
Day of Onset Melt Analysis.....	17
Analysis of C-Band SAR Parameters to Optimize Accurate	
Analysis of Onset of Melt Below Canopy.	20
3. RESULTS.....	22
Snow Accumulation	22
Microclimate	24
Onset of Melt	25
4. DISCUSSION AND CONCLUSIONS.....	30
Summary of Key Findings	30
Interpretation and Implications	31
Limitations	33
Broader Impacts	35
Recommendations for Future Research	36
REFERENCES CITED.....	38

LIST OF TABLES

Table	Page
1. Table 1. The tests used in analysis of SD in the treated and untreated forest. Levene's test of variance was conducted first to determine which test to use to compare SD across forest treatments.....	13
2. Table 2. The tests used in the analyses of temperature and relative humidity in the treated and untreated forests.	14
3. Figure 4. Map of Bozeman Municipal Watershed Project's fuel reduction project treatment area. The area with the white outline signifies the Bozeman Creek Watershed boundary. The light gray areas are where forest treatments have taken place and will take place. The blue area is where the snow depth data collection occurred.....	15
4. Table 3. The tests used in the analysis of day of onset melt in the treated and untreated forests.....	18
5. Table 4. Welch's t-test results of the variance between SD in the treated area compared to the untreated area. The $\alpha = 0.05$ and the p-values for each collection are $p < 0.05$ suggesting there is a statistically significant difference between the SD in the treated area compared to the untreated area.....	23
6. Table 5. Ablation Analysis results Normalized Mann-Whitney U results of the direction and magnitude of difference in the SAR-derived day of onset melt between the treated and untreated area. The $\alpha = 0.05$ and the p-values for each collection are $p < 0.05$ suggesting there is a statistically significant difference between the day of onset melt in the treated area compared to the untreated area. Values below 0.5 indicate earlier melt in the treated forest than the untreated forest, meaning each year except 2019 and 2023 indicate earlier melt in the treated forest compared to the untreated forest. KS test results show a similar pattern with slight but statistically significant divergence in distribution.....	28

LIST OF FIGURES

Figure	Page
7. Figure 1. Aerial image of the treated and untreated forest separated by the forest service road. This demonstrates the proximity of the treated and untreated forest and the visible differences in tree cover	2
8. Figure 2. Map of study area for LiDAR-derived snow depth collection and meteorological stations in Bozeman Creek Watershed with a map of the United States for context.....	10
9. Figure 3. Images of the study site in treated (a) and untreated (b) forest at the study area for snow depth data collection.....	11
10. Figure 5. LiDAR derived SD on top, boxplots in the middle, statistics on the bottom. The darker, blue portion of the area indicates deeper SD which consistently occurs in the treated area. The light green boxes in the boxplots represent the distribution of SD within the treated forest and the dark green boxes represent the distribution of SD in the untreated forest.....	22
11. Figure 6. Histograms of temperature and relative humidity in the treated and untreated forests. The treated datasets are similar to the untreated datasets but are statistically significantly different suggesting forest density alters microclimate variables that influence snow accumulation and ablation	24
12. Figure 7. SNOTEL SWE values from the Lick Creek station plotted with pixel counts of day of onset melt to determine if SAR-derived day of onset melt lines up with SWE patterns. Note – the temporal resolution of Sentinel 1 shifted from 12 to 24 days in 2022.	26
13. Figure 8. Boxplots of day of onset melt distributions separated by being within or outside of treatment areas. Each year except 2019 and 2023 have a slightly skewed distribution of earlier melt occurring in the treated forest compared to the untreated forest.....	27
14. Figure 9. KS test curves visualizing when the maximum divergence occurs. For each year, the maximum divergence of the two distributions tends to happen with the treated forest having earlier melt, which happens each year except 2019 and 2023. Each year had a statistically significant maximum divergence between the two dataset with the p-value < 0.05.	28
15. Figure 10. Cumulative growth curves for each year. These show cumulative proportion of pixels that have been read as beginning melt. These show a shift in the inset of melt as well as a higher growth rate in the treated forest.....	29

ABSTRACT

Forest management and thinning have implications on snowpack accumulation and melt dynamics. Changes to canopy cover alter snow interception, incoming radiation, and the cumulative energy balance. Bozeman, Montana, USA, receives up to 40% of its municipal water supply from the Bozeman Creek Watershed (45.5°N, 111°W), characterized by a densely overstocked forest that poses a high wildfire risk and subsequent impacts on the water supply. Although this watershed is of great importance and snowmelt dominated, the impacts of current forest thinning on the snowpack are not well understood. To examine how forest treatments aimed at reducing wildfire risk affect snow accumulation and melt, three key datasets with varying spatial and temporal resolutions were collected and analyzed. Measurements of snow depth from Uncrewed Aerial Vehicle (UAV) - based Light Detection and Ranging (LiDAR), weather from meteorological stations, and Sentinel-1 C-band Synthetic Aperture Radar (SAR) were collected and analyzed from treated and untreated plots of forest. SAR analysis suggests that the onset of melt initiates earlier and melts faster in the treated forest compared to the untreated forest, suggesting that the day of onset melt is influenced by canopy cover change due to forest thinning. The meteorological data also suggest a temperature or relative humidity difference between the treated and untreated forest. LiDAR-derived snow depth data demonstrate consistently more snow accumulation in the treated forest. Under current climate trends and continued land cover disturbances, this research will help shape better-informed forest management strategies that optimize forest health and water supply.

CHAPTER ONE

INTRODUCTION AND BACKGROUND

Geographic Context, Forest Management, and Water Resource
Risk

Decades of fire suppression in forests of the Western United States have led to unnaturally dense forests with greater biomass, increasing the frequency, intensity, and cost of wildfires (North et al., 2022). Recognizing the threat posed by dense forest conditions to both forest health and water resources, the City of Bozeman, Montana; USA conducted three risk assessments in 2003 and 2004 (Erickson & Seth, 2011). These assessments concluded that in the event of wildfire, sediment and ash could contaminate Bozeman's municipal water supply (Fretwell & Smith, 2021; A. Miller, n.d.). In response, the National Forest Service and the City of Bozeman developed the Bozeman Municipal Watershed (BMW) Project, a forest management plan focused on strategic thinning within the Bozeman and Hyalite Creek Watersheds. The contrast between the treated and untreated forest conditions, clearly shown in Figure 1, highlights how thinning has altered canopy structure in these adjacent stands. Because these watersheds are snow-melt dominated, altering canopy cover through forest treatments has direct implications for the hydrologic cycle, particularly snow accumulation and ablation processes (Varhola et al., 2010; Veatch et al., 2009). Even though Bozeman and Hyalite Creek Watersheds together supply approximately 80% of the city's municipal water (Fretwell & Smith, 2021), the

potential effects of forest thinning on snowpack dynamics were not addressed in the BMW Project.



Figure 1. Aerial image of the treated and untreated forest separated by the forest service road. This demonstrates the proximity of the treated and untreated forest and the visible differences in tree cover.

Snowpack Dynamics and Forest Structure

Snow Accumulation: Interception and Sublimation

Snow accumulation in forested environments is strongly driven by canopy structure (Sun et al., 2022). One of the most direct influences of forest canopy on snowpack is canopy interception, which occurs when falling snow is captured by tree canopies before reaching the ground. This process is particularly significant in dense coniferous forests, where branch structure and foliage lead to the retention of large amounts of snow (Hedstrom & Pomeroy, 1998; Storck et al., 2002). In cold, dry climates, intercepted snow sublimates, driven by low humidity,

wind exposure, and solar radiation. This can result in substantial reductions in ground-level snow accumulation, with studies estimating that 20–60% of cumulative snowfall can be lost to sublimation in these settings (Gustafson et al., 2010; Pomeroy & Essery, 1999; Sun et al., 2022).

The magnitude of interception depends on forest density. Gleason et al. (2021) demonstrate that in water-limited pine forests of the western U.S., denser stands increase interception and sublimation losses. Their study found that snowpack accumulation in denser forests was substantially lower and more sensitive to canopy structure than in treated or open areas, emphasizing the influence of forest structure on hydrology.

Goeking & Tarboton (2020) provide a broad synthesis of how forest disturbances — including thinning, fire, and beetle kill — influence snowpack and streamflow across western coniferous forests. Their review reinforces that canopy reductions typically lead to increased snow accumulation due to reduced interception and higher snowfall retention on the forest floor. However, they also caution that these effects vary widely depending on species composition, elevation, and regional climate. In the end, the geographical and resultant hydroclimatic context matters.

These findings support the importance of considering interception and sublimation when evaluating the hydrologic impacts of forest treatments. In the Bozeman Creek Watershed, where dense conifer stands dominate and winters are cold and relatively dry, interception-driven losses are likely to be significant. Despite this, the influence of forest canopy changes on snow interception was not originally assessed as part of the BMW Project’s forest treatment planning, pointing to a gap that this study seeks to address.

Snow Ablation: Radiation and Energy Balance. Forest canopy continues to influence the snowpack after accumulation by modifying the energy exchanges that drive ablation—the combined loss of snow through melt and sublimation. These processes are controlled mainly by surface energy balance components, particularly shortwave and longwave radiation, both of which are strongly shaped by forest structure (Link & Marks, 1999; Sicart et al., 2006).

The impacts of forest thinning on snowpack dynamics create trade-offs. In open areas, although more snow accumulates, more shortwave radiation reaches the snow surface, leading to faster and earlier melt out (Gleason et al., 2021; Goeking & Tarboton, 2020). Forested stands, on the other hand, reduce incoming shortwave radiation through shading but contribute more longwave radiation, especially under cloudy skies and at night (Hardy et al., 1998; Marks & Dozier, 1992). The overall effect of canopy cover on ablation depends on how these radiative inputs balance out, along with local microclimate factors like air temperature, humidity, and wind.

These patterns also vary by region (Sun et al., 2022). In maritime climates like the Pacific Northwest, frequent cloud cover and cooler temperatures can slow melt, even in forest gaps (Schnorbus et al., 2014). In contrast, continental and semi-arid regions—like much of the interior West—experience faster melt in openings due to high solar radiation and greater diurnal temperature swings (Gleason et al., 2021; Goeking & Tarboton, 2020). This variability highlights the importance of local context in predicting how thinning will affect snow accumulation and ablation.

Forest structure also shapes near-surface microclimates. Denser canopies buffer snowpacks from wind and temperature extremes, reducing turbulent heat flux and slowing melt

(Moreno et al., 2015). Open areas, by contrast, are more exposed and tend to see more rapid melt, particularly during periods with daytime thaw and nighttime refreeze (Marks & Dozier, 1992).

Together, these interactions point to the need for site-specific assessments of how changes in canopy cover influence accumulation and ablation, especially in managed forests where thinning strategies vary in scale, density, and regional setting.

Remote Sensing and Snowpack Monitoring Techniques

LiDAR for Snow Depth and Forest Structure

High-resolution snow depth measurements aid in understanding how forest structure influences snow accumulation and melt. In this study, airborne LiDAR (Light Detection and Ranging) was employed to estimate snow depth by calculating the elevation difference between snow-on and snow-free terrain surfaces. This method is widely used in snow hydrology for its accuracy across forested and complex terrain (Deems et al., 2006; Hojatimalekshah et al., 2023), and for its ability to capture the fine-scale heterogeneity often missed by in situ observations.

Uncrewed aerial vehicle (UAV)-based LiDAR is particularly effective in forested watersheds like Bozeman Creek, where snow accumulation is strongly influenced by canopy cover. Harder et al. (2020) demonstrate that even under dense canopy, LiDAR-based snow depth estimates can achieve high accuracy. In broader landscape studies, Miller et al. (2022) examined how snow depth spatial variability evolves throughout the season in complex terrain. They found that snow depth becomes increasingly heterogeneous with accumulation, and that fine-resolution measurements—like those from airborne LiDAR—are essential to represent patterns driven by vegetation, wind redistribution, and topography. These insights reinforce the capabilities of

LiDAR for capturing not just snow depth, but the spatial context of snow–canopy interactions.

LiDAR can also be used to determine leaf area index (LAI) which was identified as important to quantify in research on canopy density by Gleason et al. (2021).

Despite its advantages, LiDAR data collection comes with important limitations. Weather and cloud cover can disrupt planned flights. Additionally, while LiDAR effectively measures snow depth, it does not provide snow density or water content—so it cannot directly measure snow water equivalent (SWE). Even with these constraints, LiDAR remains one of the most effective tools for monitoring snowpack in forested environments, which makes it useful for evaluating the effects of forest treatments on snow accumulation (Krogh et al., 2020).

SAR for Snowmelt Onset

C-band synthetic aperture radar (SAR) from the Sentinel-1 satellite constellation can be used to track snowmelt onset across wide areas and multiple years. SAR is a type of active remote sensor, emitting C-band microwave signals (3.75–7.5 cm) and measuring the energy reflected from the Earth’s surface. The resultant backscatter signal changes depending on surface roughness, moisture content, and dielectric properties. In snow-covered regions, the appearance of liquid water within the snowpack produces a notable drop in backscatter due to changes in its dielectric properties, which absorb and scatter the radar signal (Marin et al., 2020).

In this study, time series from C-band SAR measurements were used to estimate the day of melt onset in each pixel in both treated and untreated forest stands. Following the approach outlined by Marin et al. (2020), melt onset was identified as the seasonal minimum in backscatter, which corresponds to the initial presence of liquid water in the snowpack for each pixel within the area of interest. This SAR analysis enabled interannual and spatial comparisons

of snowmelt timing between treated and untreated forests in the Bozeman Creek Watershed, allowing for the estimation of days of onset of melt.

C-band SAR signals interact strongly with forest canopies, leading to backscatter primarily originating from within the canopy rather than the snow surface. This reduces SAR sensitivity to ground-level snowmelt in densely forested areas, where melt onset dates may instead reflect changes in intercepted snow. As a result, the onset of SAR-derived melt estimates tends to be more reliable in open or treated stands where canopy interference is minimized. Using VV polarization can help mitigate these effects, as it is less sensitive to vegetation structure (Marin et al., 2020; Nagler et al., 2016). Despite these limitations, SAR remains a valuable tool for tracking melt dynamics—especially when integrated with complementary data sources like LiDAR and meteorological observations (Li et al., 2025).

Study Purpose and Research Questions

This research aims to quantify how forest management strategies that alter canopy cover influence snow accumulation and ablation processes in Bozeman Creek Watershed. The study addresses a key knowledge gap by linking forest treatments to snowpack dynamics in this snowpack-fed watershed—an important connection for both local water resource planning and long-term forest resilience. The overarching question guiding this work is: What is the impact of forest treatments on snow accumulation and ablation in mid-latitude, montane forests, using the Bozeman Creek Watershed as a testbed?

To address this, the study examines three key areas: snow accumulation, snow ablation, and the influence of microclimate. Specifically, it asks whether treated forests accumulate more snow than untreated areas, whether snowmelt begins earlier and progresses more rapidly in

treated stands, and whether microclimate differences contribute to these patterns. Based on prior research, the following hypotheses are tested: (1) treated areas will accumulate more snow due to reduced canopy interception; (2) melt will begin earlier in treated stands because of increased solar exposure and altered energy fluxes; (3) the rate of melt will be faster in treated areas due to reduced canopy shading; and (4) microclimate variation, particularly warmer daytime temperature, higher windspeeds, and lower humidity, will amplify ablation in treated forests.

These questions were addressed by integrating UAV-based LiDAR for snow depth and high-frequency meteorological measurements from one winter, integrated with C-band SAR for detecting melt onset from 2017 to 2024, which combined generated multi-scale, multi-year insights. The combination of high-resolution spatial and temporal datasets allows for a detailed evaluation of treatment effects across a range of canopy structures and elevations. This study's integration of remote sensing and in situ data offers a novel, context-specific assessment of forest thinning impacts on snowpack dynamics in a snow-fed watershed.

CHAPTER TWO

METHODS

Three primary datasets of different spatial and temporal resolutions were collected and analyzed to investigate how forest treatments implemented for fire mitigation influence snow accumulation and ablation. High spatial resolution LiDAR and high temporal resolution meteorological data were acquired within a study area in the Bozeman Creek Watershed during the 2024 winter and early spring to assess snow accumulation in relation to canopy cover. For the ablation analysis, broad-scale C-band SAR data from Sentinel-1 were processed for the entire watershed, covering the period from 2017 to 2024.

Snow AccumulationSite for Snow Accumulation Data Collection

Snow depth and meteorological data were collected from two adjacent plots in the Bozeman Creek Watershed: one located within a treated (thinned) forest and the other within an adjacent, untreated (unthinned) forest (Figure 2). This area received treatment in October of 2021. The study plots were similar in size, elevation, aspect, and slope, and were chosen to minimize the influence of topographic variability and to allow for a more direct assessment of canopy cover effects on snow accumulation and ablation patterns (Bales et al., 2011). Both plots were situated at approximately 45.5°N, 111°W, at a mean elevation of 1,730 meters above sea level (m.a.s.l). The dominant tree species in both areas is *Pinus contorta* (lodgepole pine).

For site context, the analysis of the LiDAR data confirmed substantial differences in canopy density between the two plots, with a mean canopy density of 0.21 in the treated forest

and 0.45 in the untreated forest. These contrasting forest structures and proximity to each other make the site well-suited for evaluating how fire-mitigation treatments alter snow dynamics.

Figures 1, 2, and 3 illustrate the structural differences between the treated and untreated plots.

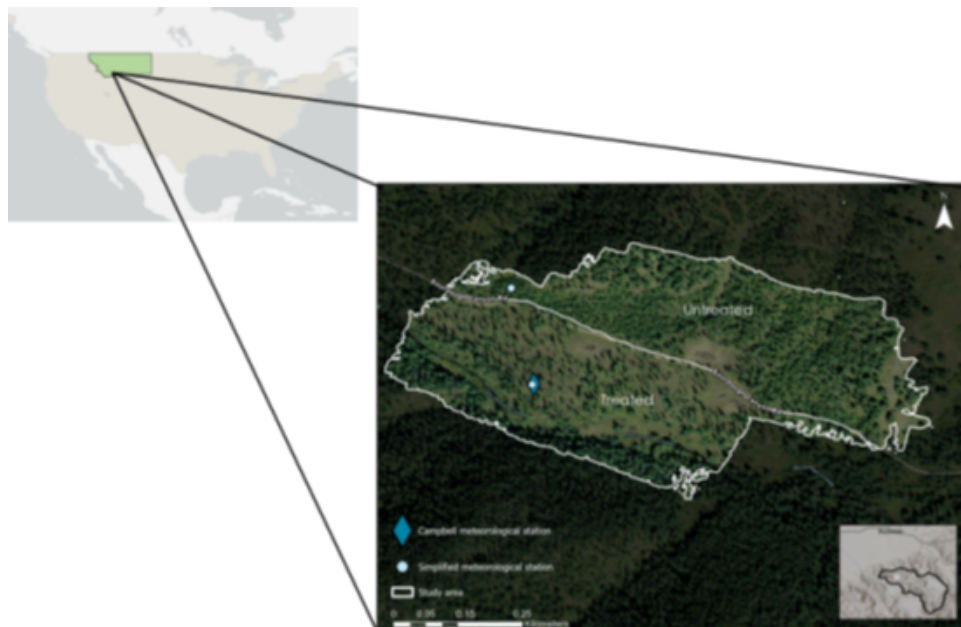


Figure 2. Map of study area for LiDAR-derived snow depth collection and meteorological stations in Bozeman Creek Watershed with a map of the United States for context.



Figure 3. Images of the study site in treated (a) and untreated (b) forest at the study area for snow depth data collection.

Snow Depth Data Collection and Analysis

Snow depth differences between treated and untreated forest areas were analyzed using data collected by a UAV-based LiDAR system (GreenValley International, LiAir V70). LiDAR measures the time delay between the emission and return of laser pulses, enabling high-resolution elevation mapping which is important to capture due to the high spatial variability of snow (Lundberg et al., 2016; Marshall et al., 2006). In this study, snow depth (SD) was calculated by differencing digital surface models obtained under snow-on and snow-off conditions (Mazzotti et al., 2019). The spatial resolution of the LiDAR data used in the analysis was 0.5 m, based on Miller et al. (2022).

UAV flights were conducted over two adjacent plots—one in the treated forest and the other in the untreated forest. These flights were performed consecutively, with less than one hour between acquisitions to minimize temporal variation in conditions. Snow-on data were collected on January 28, February 22, March 18, March 20, and March 28 of 2024, and snow-off data were

collected on May 17, 2024. The flight on February 22 was limited due to weather and mechanical error.

Snow depth collection in this area was conducted for only one season, due to the project's scope. This season was unusually warm and dry for this area. The Lick Creek SNOTEL site, which is in an adjacent basin, recorded 55 of the 60 days in January and February as record lows for snow water equivalent (SWE) and the temperatures were 1.8° C warmer than average from January to February 2024 (NRCS, 2024).

Raw LiDAR data were preprocessed using LiDAR360 and LiGeoreference software. To ensure spatial accuracy, Global Positioning System (GPS) units were deployed during each UAV flight, and a local GNSS (Global Navigation Satellite System) Precise Point Positioning (PPP) reference site was used to improve geolocation accuracy.

Post-processing was conducted in ArcGIS Pro to generate five SD layers by subtracting the snow-off LiDAR-measured surface from each snow-on acquisition. A baseline ground datum was applied to have a minimum SD of 0 m and a maximum SD of 1 m to filter for false returns. These SD layers were then spatially subsetted to the treated and untreated study sites for statistical comparison.

To assess whether snow depth differences between treatments were statistically significant, independent two-sample t-tests, or Welch's t-tests were conducted (Table 1). Prior to each test, Levene's test was used to evaluate the assumption of equal variances. All statistical analyses were performed in Python on Montana State University's High-Performance Computing (HPC) system, with a significance threshold of $\alpha = 0.05$.

Test	Description	Data Tested
Levene's test of Variance	Assess equality of variances between two or more groups (Levene, 1960)	Determine if the variances in SD between the treated and untreated forest were equal to determine which test to use to conduct on SD in treated and untreated forests
Welch's t-test	Compares means of two-independent groups (Welch, 1947)	Compare mean SDs due to unequal variances and sample sizes

Table 1. The tests used in analysis of SD in the treated and untreated forest. Levene's test of variance was conducted first to determine which test to use to compare SD across forest treatments.

Microclimate

To assess the influence of forest canopy cover on local microclimate conditions relevant to snow accumulation and ablation, meteorological data were collected in both treated and untreated forest plots. Two stations were deployed—one in each plot—to record temperature, relative humidity, wind speed, wind direction, and wind gusts (locations shown in Figure 2). Temperature and relative humidity were measured using HOBO Pro v2 sensors, and wind data were collected using Rainwise WindLog sensors.

A Campbell Scientific meteorological station was installed near the HOBO and Rainwise-based system in the treated forest to provide validation and a more comprehensive dataset. This station recorded temperature, relative humidity, wind speed, wind direction, wind gusts, albedo, and snow depth. All sensors were operational from October 8, 2023, through April 24, 2024 (snow off).

Statistical analyses, including Wilcoxon signed-rank tests and linear regressions, were conducted to determine whether significant differences in meteorological conditions existed

between the treated and untreated forests. These comparisons were used to evaluate whether variations in localized meteorological variables, potentially influenced by canopy structure, could account for observed differences in snow accumulation (Table 2)

Test	Description	Data Tested
Shapiro-Wilk test	Tests a dataset's distribution for normalization (Shapiro & Wilk, 1965)	Determine which test to conduct between temperature and relative humidity measurements in the treated and untreated forests
Wilcoxon-signed rank test	Non-parametric test to compare related samples by mean ranks for non-normally distributed data (Wilcoxon, 1945)	Assess how mean ranks of temperature and relative humidity differ in treated and untreated forest
Linear regression	Examine a relationship and correlation between two datasets (Montgomery et al., 2012)	Quantify the strength of the association between temperature and relative humidity in the treated and untreated forests

Table 2. The tests used in the analyses of temperature and relative humidity in the treated and untreated forests.

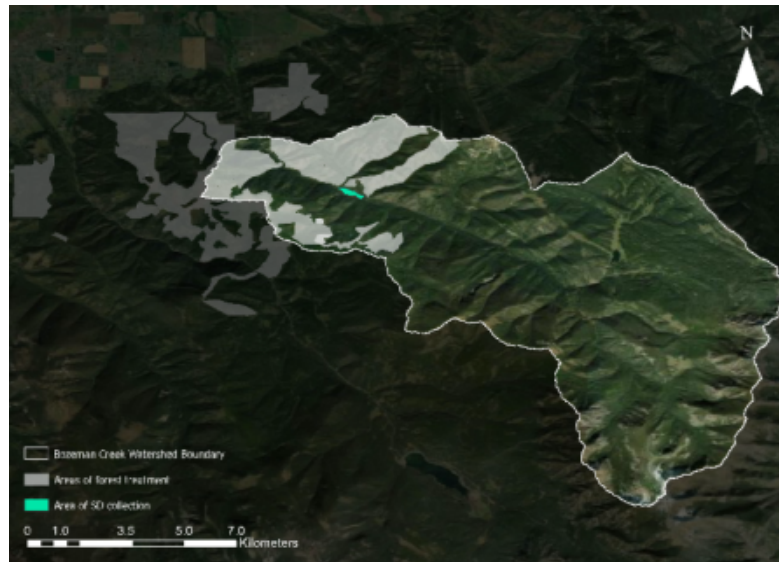
AblationStudy Site for Snow Ablation

Figure 4. Map of Bozeman Municipal Watershed Project’s fuel reduction project treatment area. The area with the white outline signifies the Bozeman Creek Watershed boundary. The light gray areas are where forest treatments have taken place and will take place. The blue area is where the snow depth data collection occurred.

Analysis of snow ablation was conducted across the entire Bozeman Creek Watershed. The Bozeman Municipal Watershed Project – developed by the City of Bozeman and the National Forest Service (NFS) – encompasses both Bozeman and Hyalite Creek Watersheds, which supply up to 80% of Bozeman’s municipal water (Fretwell & Smith, 2021). Hyalite Watershed is relatively well monitored with two SNOTEL sites and a stream gauge, while Bozeman Creek Watershed has just one stream gauge. Due to the lack of monitoring in the Bozeman Creek Watershed, this study focuses exclusively on the Bozeman Creek Watershed, rather than all treatment areas. As shown in Figure 4, the area of forest treatments occurred near

the mouth of Bozeman Creek Watershed utilizing various techniques of forest treatments including fuelbreak, helicopter, broadcast burn, and mechanical and/or non-mechanical thinning. This project is ongoing and in multiple iterations, so not all areas identified for treatment have been completed.

Day of Onset Melt Data Acquisition

The onset of snowmelt signals when snowpack begins releasing water and provides insight into how long snow will persist into spring (Gagliano et al., 2023). Since forest canopy density strongly influences snowmelt timing by altering the energy balance, forest treatments that reduce canopy cover are expected to impact the timing and rate of melt (Ellis et al., 2013; Lewis et al., 2023; Sun et al., 2022; Varhola et al., 2010). Depending on local climate conditions, reduced canopy cover may either accelerate or delay melt: trees can protect snow from incoming shortwave radiation or enhance melt via longwave radiation emissions from the canopy (Bales et al., 2011; Hedstrom & Pomeroy, 1998; Zheng et al., 2018).

To evaluate the impact of forest treatments on snowmelt dynamics, this study estimated the day of onset melt using Sentinel-1 C-band synthetic aperture radar (SAR) data. C-band SAR is sensitive to changes in snowpack structure and liquid water content. During the accumulation season, dry snow exhibits volume scattering, which results in a relatively stable SAR backscatter signal. As the snowpack ripens and begins to melt, the increased liquid water content leads to absorption of the radar signal and a notable drop in backscatter. The date of this local minimum in backscatter was interpreted as the day of melt onset for each 10 m pixel located within the watershed (Marin et al., 2020).

Sentinel-1 consists of satellites Sentinel-1A and Sentinel-1B. Prior to the failure of Sentinel-1B in 2022, the constellation offered a 12-day revisit time; afterward, the temporal resolution decreased to 24 days. While coarse, this resolution can provide valuable insights (Gagliano et al., 2023). For this analysis, the day of onset melt was defined as the date corresponding to the lowest SAR return during the melt season, based on this temporal frequency.

SAR data for the years 2017 to 2024 were acquired using a combination of Python packages accessed through Microsoft's now-retired Planetary Computer Hub. Tools developed by Gagliano et al. (2023) were also used to streamline data acquisition and processing. A GeoJSON boundary of the Bozeman Creek Watershed was prepared and reprojected to match the SAR data's coordinate reference system (CRS). This watershed boundary was then used to spatially clip the SAR imagery, ensuring efficient and targeted processing. The melt season was defined as February 1 to May 31 for each year. For each SAR image during this window, backscatter values were analyzed at the pixel level to identify the date with the minimum return, which was recorded as the day of onset melt.

Day of Onset Melt Data Analysis

The analysis of the C-band SAR derived day of onset melt data began by separating the pixels within and outside of the treatment areas within the watershed. The data was separated by forest treatment in ArcGIS Pro using geometries supplied by the NFS' forest treatment plan for the Bozeman Municipal Watershed Project (BMW).

Before analyzing the day of onset melt, snow water equivalent (SWE) data were analyzed from the Lick Creek SNOTEL site, the closest automated site located in the adjacent watershed

to test if the day of onset melt values corresponded to SWE values temporally, indicating if the SAR-derived data were accurate for each year. Since the SAR-derived day of onset melt counts aligned with SWE values that are indicative of accurate data acquisition, the question of how forest treatments impact ablation could be addressed.

Test	Description	Data Tested
Shapiro-Wilk test	Tests distribution of a dataset for Normalization (Shapiro & Wilk, 1965)	SAR-derived day of onset melt to determine which test to use to compare
Normalized Mann-Whitney U Test	Non-parametric test that compares differences in central tendency for non-normally distributed and independent datasets (Zar, 1999)	Quantify the extent to which the distributions in the day of onset melt are separated between the treated and untreated forests
Kolmogorov-Smirnov Test	Non-parametric test that evaluates maximum divergence between two groups and if they were drawn from the same distribution (Conover & Conover, 1999)	Assess how much of a difference exists between day of onset melt between the treated and untreated forests

Table 3. The tests used in the analysis of day of onset melt in the treated and untreated forests

Each statistical analysis performed has a significance level (α) of 0.05 to evaluate the statistical significance of the results. The initial exploratory analysis involved visualizing the distribution of onset melt dates using boxplots to provide an overview of variability across and between treated and untreated forest areas. Given that the datasets are independent and do not follow a normal distribution, Mann–Whitney U tests were conducted for each year to assess whether the distributions of melt onset dates in treated and untreated forests differ significantly. The U statistic, derived from ranked data, quantifies the extent to which the two distributions are

separated (Zar, 1999). However, as the raw U value is influenced by sample size, a normalized U statistic was computed using the equation:

$$\text{Normalized } U = \frac{U}{n_1 * n_2}$$

This normalization facilitated comparison across years and provided a standardized indication of the direction and magnitude of differences in melt onset timing—specifically, whether snow tends to melt earlier in treated or untreated forests (Sheskin, 2020; Zhang et al., 2017).

To further examine differences in distribution, Kolmogorov–Smirnov (KS) tests were applied. The KS test is non-parametric and evaluates the maximum divergence between the empirical cumulative distribution functions (ECDFs) of the two groups and tests if the samples are drawn from the same distribution (Conover & Conover, 1999; Massey, 1951). KS test curves were also used to visualize and interpret the extent and timing of maximum difference in melt timing distributions between treatment types.

As a complementary analysis and visualization strategy, cumulative melt progression curves were generated for both treated and untreated areas. These curves plotted the cumulative percentage of pixels that had reached melt onset during the melt season (February 1–May 31), enabling direct comparison of the timing and pace of snowmelt progression across forest treatments. The y-axis represents the proportion of pixels within each treatment class that had initiated melt, offering a landscape-scale perspective on how forest thinning may accelerate, or delay melt onset. This approach provided a clear visual representation of melt timing differences and helped contextualize the statistical findings, reinforcing the connection between canopy alteration and spatial variability in snow ablation.

Analysis of C-Band SAR Parameters to Optimize Accurate Analysis of Onset of Melt Below Canopy. C-band SAR has been proven to perform well in detecting the onset of snowmelt on flat, open ground (Marin et al., 2020). However, it is well documented that C-band SAR has difficulties detecting information beneath a canopy (Marin et al., 2020). As this analysis is focused on changes in forest canopy impacting the snow beneath the canopy, it is important to ensure the results of the analysis are not a function of poor data acquisition and rather, returns outputs as close to reality as possible.

Polarization and spatial resolution can be adjusted to minimize the impacts of the presence of a canopy in detecting the presence of liquid water beneath a canopy. Polarization is the orientation of the signal's oscillations. The two polarizations tested for optimal data quality are vertical-vertical (VV) and vertical-horizontal (VH). VV polarization sends a signal vertically toward the surface of the earth and receive a signal vertically. VH polarization sends a signal vertically and receives a signal horizontally. VV has been shown to detect beneath canopy features better than VH due to the geometry of trees (Escobar-Ruiz et al., 2023; Gagliano et al., 2023). Therefore, VV polarization was used for the analysis of the day of onset melt.

Spatial resolution is the size of the areas the sensor can distinguish or the level of detail and can impact the data by smoothing important details if the resolution is too coarse or create noise if the resolution is too fine. Coarser resolution allows for more efficient run-time for analyses but may not detect subcanopy variation. To determine which spatial resolution to use for analysis, a Moran's I statistical test was run for each year to test if similar values are spatially

clustered, and in this case, if one resolution shows a more meaningful spatial structure than the other.

The results of the Moran's I test indicate spatial clustering of similar values for both spatial resolutions, with values of approximately 0.63 for the 5-meter resolution and 0.33 for the 10-meter resolution (Supplemental Table 1). This suggests that the 5-meter data capture more localized spatial patterns and exhibit stronger spatial autocorrelation. However, despite the higher clustering at finer resolution, the difference in Moran's I was not substantial enough to justify the increased computational demand associated with the 5-meter data. The 10-meter resolution was deemed sufficient to represent meaningful spatial structure while offering greater efficiency for large-scale analysis. As a result, the 10-meter resolution and VV polarization were selected for continued analysis of the day of onset melt.

CHAPTER THREE

RESULTS

Snow Accumulation

UAV-based LiDAR analysis revealed that treated forest areas consistently accumulated more snow than untreated areas, particularly as the season progressed. This pattern is attributed to reduced canopy interception in treated stands. In the untreated forests, snow is intercepted by the canopy and may sublimate before reaching the ground, reducing the amount of snow contributing to the local water supply. In contrast, treated areas—with more open canopy—experience less interception, allowing for greater snow accumulation.

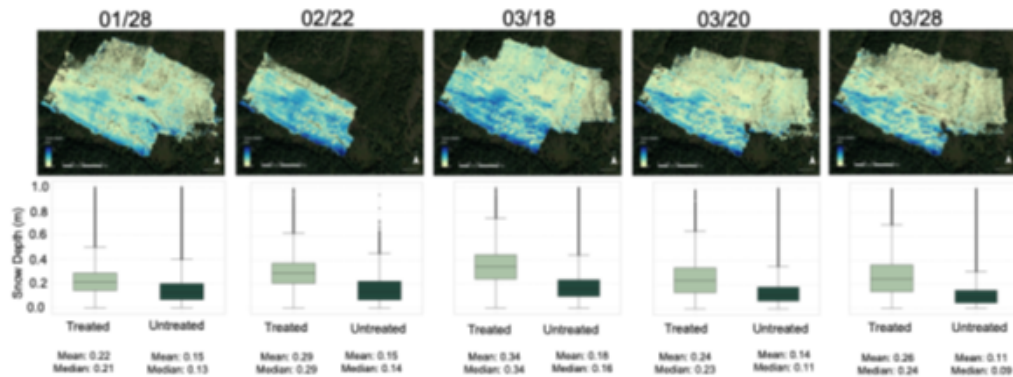


Figure 5. LiDAR derived SD on top, boxplots in the middle, statistics on the bottom. The darker, blue portion of the area indicates deeper SD which consistently occurs in the treated area. The light green boxes in the boxplots represent the distribution of SD within the treated forest and the dark green boxes represent the distribution of SD in the untreated forest.

These trends are clearly illustrated in the spatial SD maps boxplots and statistical outputs in Figure 5. The LiDAR-derived SD plots consistently show deeper snow in the treated plots (lower portion of the map, with snow depths indicated by darker blue hues) and shallower snow in the untreated plots (upper portion of the map, with snow depths indicated by lighter shades). Corresponding boxplots further demonstrate that the treated forest has a higher median and mean SD across all five snow-on collection dates. Distributions are consistently skewed higher in the treated forest, indicating more overall snow depth. Outliers are expected due to the high spatial resolution of the LiDAR data.

Levene's tests (Table 3 Supplemental figures) indicated unequal variances between treated and untreated forests ($p < 0.05$), so Welch's t-tests were used to compare mean snow depth (SD) for each collection date. Results (Table 4) showed consistently higher mean SD in treated areas ($p < 0.05$), suggesting that forest treatments for fire mitigation significantly increases snow accumulation. This effect was observed in a study area with minimal topographic variation, highlighting canopy cover as the main factor driving these differences.

	01/28	02/22	03/18	03/20	03/28
Welch's t-statistic	240.6	212.5	450.3	309.9	390.7

Table 4. Welch's t-test results of the variance between SD in the treated area compared to the untreated area. The $\alpha = 0.05$ and the p-values for each collection are $p < 0.05$ suggesting there is a statistically significant difference between the SD in the treated area compared to the untreated area.

Microclimate

The Shapiro-Wilk test indicated that temperature and relative humidity data in both the treated and untreated forests were not normally distributed. As a result, Wilcoxon signed-rank tests were conducted and revealed statistically significant differences in both variables ($p < 0.05$ for both; Supplemental Table 4). These findings suggest that canopy structure may influence microclimate conditions that influence snow accumulation and ablation.

Linear regression analyses showed strong correlations between treated and untreated sites for both temperature (slope = 0.98, $R^2 = 0.98$) and relative humidity (slope = 0.89, $R^2 = 0.98$). Despite the high correlations, the treated forest consistently exhibited slightly higher temperatures and lower relative humidity than the untreated forest. These patterns are further illustrated in summary statistics (Table 2) and the relative humidity and air temperature histograms (Figure 6).

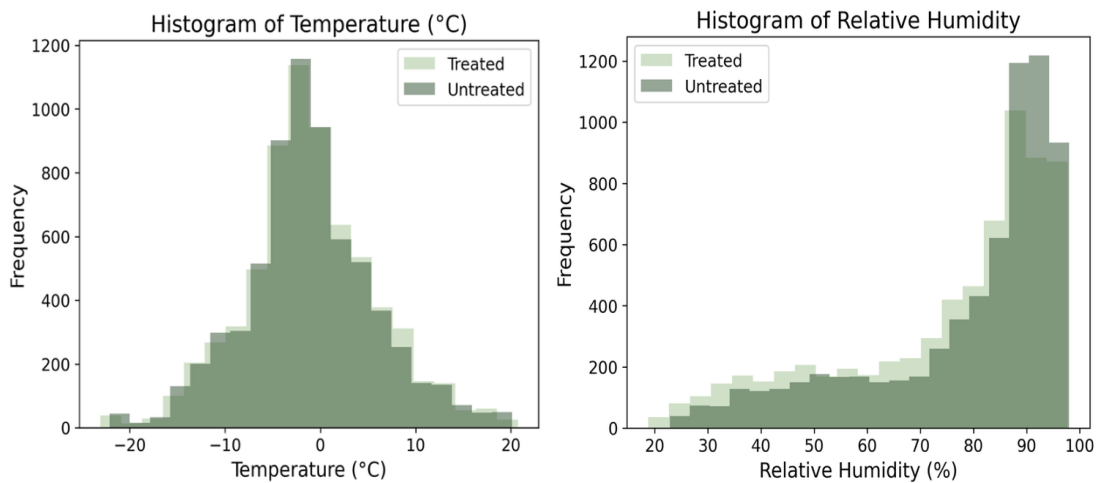


Figure 6. Histograms of temperature and relative humidity in the treated and untreated forests. The treated datasets are similar to the untreated datasets but are statistically significantly

different suggesting forest density alters microclimate variables that influence snow accumulation and ablation

Summary statistics for temperature and relative humidity in the treated and untreated forests indicate slightly higher mean temperatures in the treated forest ($-1.05\text{ }^{\circ}\text{C}$ vs. $-1.09\text{ }^{\circ}\text{C}$) and slightly higher mean relative humidity in the untreated forest (75.0% vs. 78.8%) (Supplemental Tables 5 and 6). These patterns may reflect microclimatic differences related to canopy structure, where warmer conditions in the treated area could contribute to earlier snowmelt, while higher humidity in the untreated forest may limit sublimation.

Together, these meteorological results indicate that forest thinning leads to modest but statistically significant microclimatic conditions between the treated and untreated forests. These findings suggest the shifts that may contribute to differences in snow accumulation and melt dynamics.

Onset of Melt

To assess the temporal accuracy of the C-band SAR-derived day of onset melt, snow water equivalent (SWE) data from the Lick Creek SNOTEL site were analyzed. Although located in an adjacent watershed, Lick Creek is the closest automated snow measurements and shares similar elevation and climatic characteristics with Bozeman Creek. Pixel counts of day of onset melt were plotted alongside SWE values over time. These plots show that as SWE values decrease, pixel counts indicating onset of melt increase (Figure 7)—an expected relationship that suggests the SAR-derived melt estimates are temporally reasonable for comparison. However, because there are no SNOTEL sites within Bozeman Creek itself, direct validation is not possible, and these findings provide supporting evidence indicative of data reliability

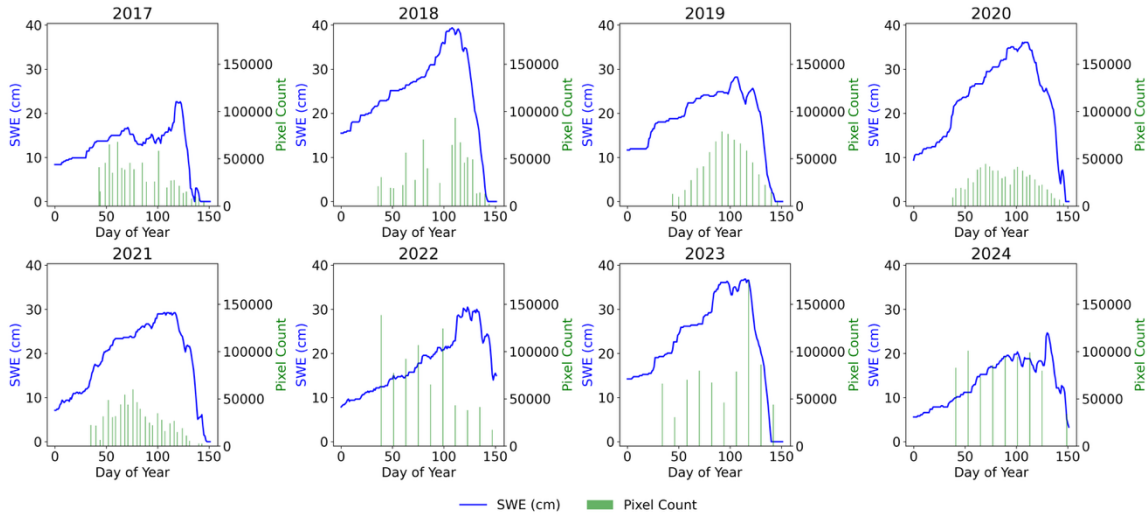


Figure 7. SNOTEL SWE values from the Lick Creek station plotted with pixel counts of day of onset melt to determine if SAR-derived day of onset melt lines up with SWE patterns. Note – the temporal resolution of Sentinel 1 shifted from 12 to 24 days in 2022.

Boxplots (Figure 8) illustrate that the distribution of day of onset melt is consistently skewed earlier in the treated forest compared to the untreated forest. Mann–Whitney U tests for all years (2017–2024) yielded p-values below 0.05, indicating significant differences in snow melt. Normalized U values were used to interpret the direction and magnitude of this shift. A normalized U value of 0.5 suggests similar distributions between groups, while values below 0.5 indicate that onset of melt occurred earlier in the treated areas. Every year except 2019 and 2023 had normalized U values below 0.5, supporting the observation that forest thinning tends to lead to earlier snowmelt.

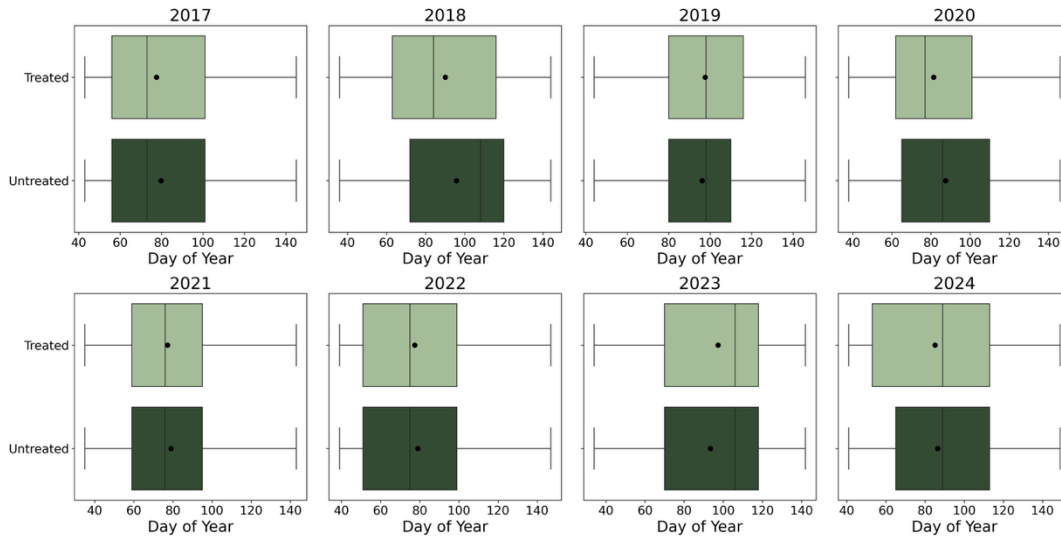


Figure 8. Boxplots of day of onset melt distributions separated by being within or outside of treatment areas. Each year except 2019 and 2023 have a slightly skewed distribution of earlier melt occurring in the treated forest compared to the untreated forest.

Kolmogorov–Smirnov (KS) tests identified the maximum difference between the cumulative distributions of melt onset dates in treated and untreated areas. While the KS statistics for each year were relatively small (all < 0.1), all tests returned statistically significant p-values (< 0.05), confirming measurable differences in the distributions. In line with the Mann–Whitney results, KS test results indicated that melt onset was earlier in the treated forest each year, except 2019 and 2023 (Table 5 & Figure 9)

	2017	2018	2019	2020	2021	2022	2023	2024
Normalized Mann-Whitney U	0.479	0.444	0.519	0.432	0.481	0.489	0.532	0.488
KS Stat	0.041	0.094	0.030	0.091	0.036	0.032	0.090	0.025

Table 5. Ablation Analysis results Normalized Mann-Whitney U results of the direction and magnitude of difference in the SAR-derived day of onset melt between the treated and untreated area. The $\alpha = 0.05$ and the p-values for each collection are $p < 0.05$ suggesting there is a statistically significant difference between the day of onset melt in the treated area compared to the untreated area. Values below 0.5 indicate earlier melt in the treated forest than the untreated forest, meaning each year except 2019 and 2023 indicate earlier melt in the treated forest compared to the untreated forest. KS test results show a similar pattern with slight but statistically significant divergence in distribution.

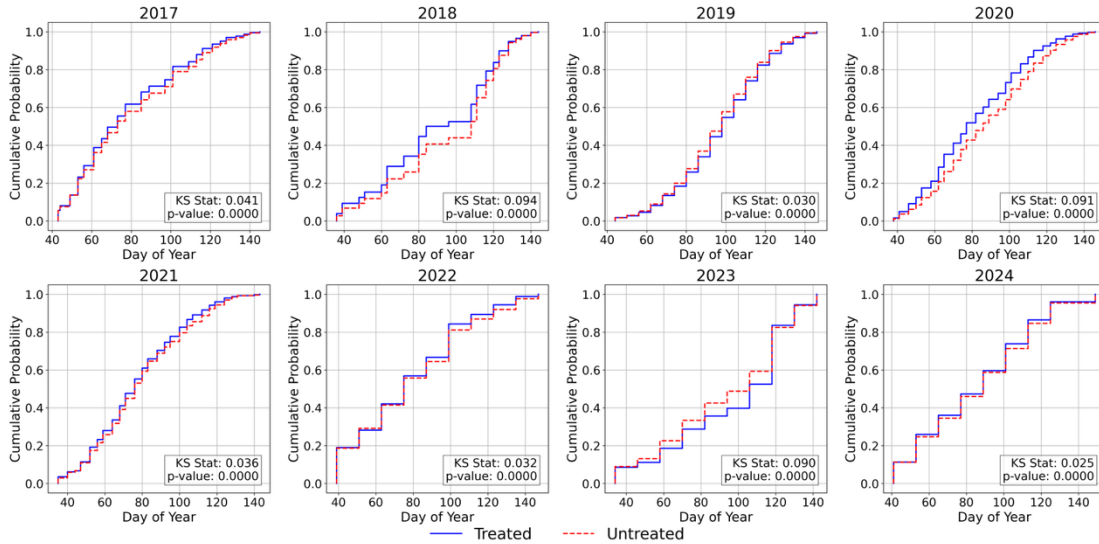


Figure 9. KS test curves visualizing when the maximum divergence occurs. For each year, the maximum divergence of the two distributions tends to happen with the treated forest having earlier melt, which happens each year except 2019 and 2023. Each year had a statistically significant maximum divergence between the two dataset with the p-value < 0.05 .

Cumulative growth curves were created to visualize the proportion of pixels in treated and untreated forests that had begun to melt over the course of each melt season (Figure 10).

These curves clearly show shifts in melt onset, rate, and overall progression. For all years from 2017 to 2024 (excluding 2019 and 2023), the treated forest exhibited an earlier onset of melt and a steeper growth curve, indicating a faster melt rate. The 2019 and 2023 curves diverged from this pattern, with melt beginning earlier in the untreated areas.

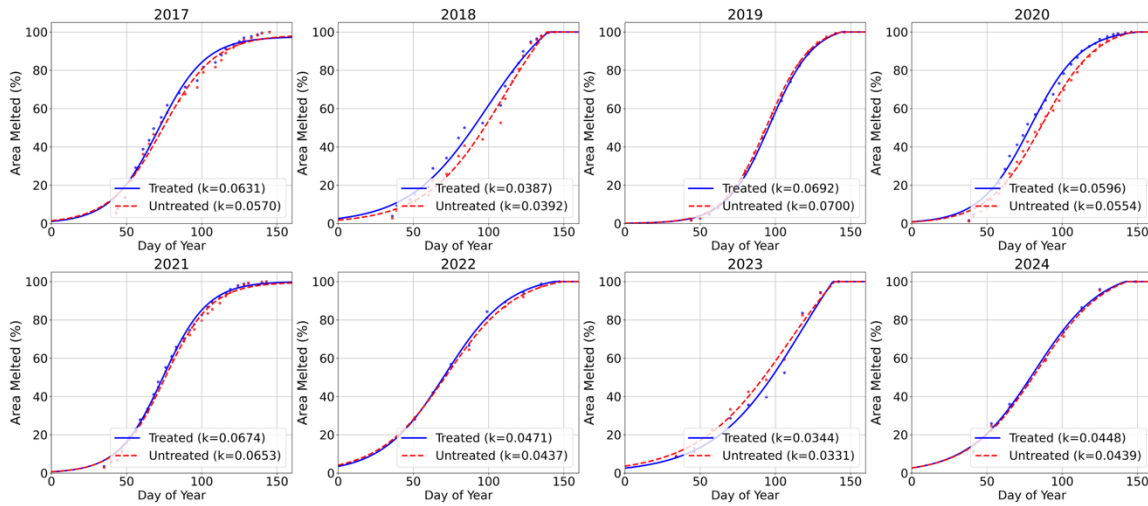


Figure 10. Cumulative growth curves for each year. These show cumulative proportion of pixels that have been read as beginning melt. These show a shift in the inset of melt as well as a higher growth rate in the treated forest

The C-band SAR-derived estimates of snow ablation indicate a consistent and statistically significant pattern of earlier melt in the treated forests compared to untreated areas. This pattern is supported by multiple analytical approaches, including SNOTEL comparison, distributional tests (Normalized Mann–Whitney U and KS), and cumulative progression curves. Exceptions in 2019 and 2023 suggest that interannual variability may influence melt dynamics. Overall, the results indicate that forest treatments that reduce canopy cover lead to earlier and more rapid snowmelt in the Bozeman Creek Watershed.

CHAPTER THREE

DISCUSSION AND CONCLUSIONS

Summary of Key Findings

This study set out to understand how forest treatments impact snow accumulation and ablation processes in a mid-latitude, montane watershed by exploring microclimate differences using meteorological data, snow depth from UAV LiDAR, and day of onset melt derived from C-band SAR. The integration of these diverse datasets enabled a multi-scale assessment of how forest canopy alterations affect snowpack dynamics in a snow-dominated watershed. The results reveal statistically significant differences in key meteorological variables—such as net radiation and air temperature—between treated and untreated forest areas, pointing to a measurable shift in microclimate driven by canopy thinning. UAV LiDAR data consistently showed greater snow accumulation in treated forests, while SAR-derived melt onset dates tended to be earlier, and melt progressed more rapidly, in these same areas.

These findings suggest a dual effect: forest thinning increases snow accumulation by allowing more snowfall to reach the ground, yet also accelerates snowmelt by exposing the snowpack to increased solar radiation and wind. This altered energy balance underscores the complexity of forest-snow interactions and highlights the importance of evaluating both accumulation and ablation processes in tandem. Statistical analyses—including Mann–Whitney U tests and Welch’s t-tests—confirmed the significance of these differences across multiple years, strengthening the case for a consistent treatment effect across inherent seasonal variability.

Together, these results help answer the study's core question: forest treatments do impact snow processes, but the impacts are nuanced. While increased snow accumulation in treated areas may support water supply goals, earlier and faster melt could offset some of these benefits by shifting runoff timing. These insights are especially critical in snow-fed municipal watersheds like Bozeman Creek, where forest management decisions have cascading ecological and societal consequences. This study contributes a replicable workflow for evaluating treatment effects and lays the groundwork for more informed, hydrologically-integrated forest management strategies.

Interpretation and Implications

These findings underscore the importance of integrating snowpack dynamics into forest treatment planning, particularly in regions where snowmelt is a primary contributor to water supply. In snow-dominated basins, forest management decisions extend beyond ecological and fire-related outcomes—they directly influence the timing and magnitude of water availability for downstream communities. While forest thinning is effective in reducing canopy interception and thereby enhancing snow accumulation, it simultaneously alters the forest energy balance. By increasing exposure to shortwave radiation and wind, thinning accelerates the timing and rate of snowmelt, potentially leading to earlier runoff and a shorter duration of snow cover.

This dual outcome—more snow accumulating, but melting sooner—has important hydrologic and ecological implications. Earlier and faster melt can shift peak streamflow to earlier in the spring, potentially increasing flood risk when melt coincides with saturated soils or spring storms. Conversely, it may reduce water availability in late summer when demand is highest, contributing to drought stress for ecosystems and communities. This risk tradeoff suggests that thinning, while beneficial for wildfire mitigation and even short-term water supply,

may unintentionally undermine longer-term water security in water-limited regions. Ultimately, the magnitude and direction of these impacts are highly dependent on the scale of treatment and the specific characteristics of the forest, including its location, elevation, and climatic context—underscoring the need for site-specific planning in forest and water management strategies.

The patterns observed in this study are consistent with existing literature that identifies shortwave radiation as a dominant driver of snowmelt in forested environments in the Continental United States. Increased snow depth in treated areas aligns with studies showing that reduced canopy cover allows greater snowfall deposition, while earlier melt reflects findings that emphasize canopy's role in moderating energy exchange at the snow surface. Together, these results reinforce the importance of forest structure in controlling both the quantity and timing of snow-derived water inputs.

In the broader context of sub-alpine forest hydrology, this research is particularly relevant to municipalities like Bozeman that depend on snow-fed, forested watersheds. It highlights the need for forest treatment strategies that go beyond fire risk reduction and consider hydrologic outcomes as a central planning standard. As seasonal hydroclimatic variability intensifies and water resources become more unpredictable, forest managers must weigh tradeoffs between snow retention, runoff timing, and water availability.

From a policy and land management perspective, these findings argue for a more integrated approach—one that treats snow as a managed resource. Future forest treatment plans in hydrologically significant areas should explicitly assess potential impacts on snow accumulation and ablation processes. Doing so would help ensure that fuel reduction goals are

balanced with the need to maintain reliable water supplies, particularly in the face of increasing demand and environmental stressors.

Limitations

Several limitations affected the depth, resolution, and certainty of this analysis. One major constraint was the absence of shortwave radiation data, which would have enabled a more detailed assessment of energy balance differences between treated and untreated forest areas. Although meteorological sensors were deployed, instrumentation failure prevented the collection of this key variable, limiting direct conclusions about radiative forcing and its role in snowmelt timing.

The UAV LiDAR dataset provided high-resolution snow depth data but lacked SWE measurements, which are essential for understanding the true water content of the snowpack. This constrains the ability to estimate the amount of water stored and released from the system. Furthermore, LiDAR performance may have been uneven across forest types. In untreated forests, dense canopy cover can attenuate laser returns, potentially leading to underestimation of snow depth. Similarly, factors like spring vegetation emergence and snow unloading may have contributed noise to snow-off measurements.

The temporal resolution of the SAR data posed a notable limitation. With a revisit time of approximately 12 days, Sentinel-1 C-band SAR may have missed critical short-term changes in melt onset, especially in years when melt transitions occurred rapidly. This coarse interval makes it difficult to detect subtle timing differences between treated and untreated forests, potentially obscuring meaningful distinctions in melt dynamics. Furthermore, C-band SAR has limited

ability to penetrate dense forest canopy, meaning the observed backscatter changes likely represent a generalized surface response rather than precise ground-level melt conditions.

Another important limitation lies in the spatial comparability of treated and untreated areas. Elevation was not systematically controlled for between the two forest types, and many treated plots were located at lower elevations where snow tends to melt earlier due to temperature gradients. This elevation bias may partially explain observed differences in melt timing. Compounding this, the forest treatments themselves were implemented on a rolling basis—some plots classified as “treated” may not have been fully thinned at the time of snowpack observation, introducing ambiguity into the treatment classification.

Each component of the study verified the same conclusions, and the observed patterns are meaningful. However, in general they should be interpreted as a well verified trend, rather than a specific, quantitative metric. Future, more intensive studies would include more robust energy balance data, finer temporal resolution SAR or optical imagery, SWE data, and better spatial controls—particularly for elevation—to help resolve uncertainties and more definitively quantify snowpack changes due to canopy treatments.

Despite these limitations, it’s important to recognize that this research represents the first study of its kind conducted in the Bozeman Municipal Watershed, and in this region of the Missouri River Headwaters. The analysis was designed not only to explore specific forest-snow interactions but also to highlight a critical oversight in how forest management plans currently account for snowpack dynamics. These limitations are expected in pioneering work of this nature and should be viewed as opportunities for refinement in future studies rather than as

shortcomings. The insights gained here establish a crucial foundation for more detailed and controlled investigations moving forward.

Broader Impacts

Despite these limitations, this research offers meaningful insight that can inform policy, land management, and public understanding at the intersection of forest management and water resources. It emphasizes the importance of integrating snowpack and hydrologic dynamics into forest treatment decisions—especially in growing communities like Bozeman, where water demand is increasing and climatic trends may further strain supply. The findings underscore that thinning alters not only wildfire risk, but also snowpack behavior, with downstream consequences for streamflow timing, water storage, and seasonal water availability.

These results are especially relevant for agencies such as the City of Bozeman and the U.S. Forest Service, which are actively engaged in forest restoration and watershed protection. By quantifying how forest treatments affect snow accumulation and melt timing, this research supports more holistic planning that considers both fire mitigation and water sustainability.

More broadly, this work contributes to regional conversations across the western United States, where communities face growing challenges from wildfire and water insecurity. As snowpack declines and precipitation patterns shift, forest management decisions will increasingly influence watershed-scale hydrology.

Importantly, this project also helps to raise awareness of a critical but often overlooked issue: the relationship between forest structure and snowpack dynamics at the watershed scale. As the first study of its kind in the Bozeman Municipal Watershed, it sets the stage for future work, offering a methodological blueprint and highlighting key variables to monitor. In doing so,

it contributes to a more nuanced, systems-level understanding of how ecological restoration intersects with water resource management.

Recommendations for Future Research

Future research should continue monitoring this basin using the workflow developed in this study, while expanding both the temporal scale and the range of variables collected. As the first study to directly examine how forest thinning affects snow accumulation and ablation in the Bozeman Municipal Watershed, this work serves as a necessary starting point for more extensive investigations. It highlights a critical knowledge gap: while fire risk reduction has been the primary driver of forest treatments, snowpack dynamics have not been fully considered in management planning or risk assessments. Addressing this oversight is especially important in snow-dominated watersheds where timing and volume of meltwater are essential to ecosystem function and human water use.

To build on this foundation, future studies should extend monitoring across multiple years and include forests with varying canopy densities, elevations, treatment intensities, and topographic complexity. Expanding spatial coverage will help clarify how generalizable these findings are beyond the specific study plots. Additionally, incorporating measurements of snow water equivalent (SWE), shortwave and longwave radiation, soil moisture, and other components of the energy balance would significantly strengthen the analytical framework. These additions would allow researchers to better understand the physical mechanisms driving the observed changes in snowpack behavior and assess how they interact under different climatic and forest conditions.

A key question emerging from this study is whether there is an optimal forest density that balances wildfire mitigation with water supply sustainability. Answering this question will require broader-scale, long-term studies that track snow processes across a gradient of forest structures and environmental conditions. Such work would help refine forest management practices by identifying thresholds beyond which thinning no longer yields hydrologic benefits or introduces tradeoffs.

New satellite missions like NASA–ISRO’s Synthetic Aperture Radar (NISAR) and continued development of UAV-based snow monitoring technologies offer promising avenues for collecting more frequent, high-resolution data. Leveraging these tools will enable researchers to track subtle, short-term changes in snowpack and assess their long-term implications at the watershed scale.

Ultimately, this study sets the groundwork for a more integrated approach to forest and water management. By demonstrating that forest thinning can alter snow accumulation and melt patterns, it underscores the importance of considering hydrologic outcomes in forest treatment planning. Continued interdisciplinary research in this area will be vital for designing adaptive, climate-resilient strategies that safeguard both ecosystem health and water security in the western U.S.

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